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**Research Institute for Laser Physics
&
Company Lasers and Optical System, Ltd.**

**STUDIES OF POSSIBILITY OF DYNAMIC CORRECTION FOR
DISTORTIONS IN MID-IR RANGE OF SPECTRUM, USING
OPTICALLY ADDRESSED LC SLM CORRECTOR AND DYNAMIC
HOLOGRAPHIC CONVERTER**

Final Report

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Introduction

This document is the Final Report on the Contract between Dr. Vladimir Venediktov as Principal Investigator working through LOS LTD located in St.-Petersburg, Russia and EOARD located in London, UK, and it covers the works ordered by the second stage of the Contract # F61775-99-WE017.

- One the first stage of the work it was shown that there exists a new and very prospective application of thin dynamic holograms, which can be efficiently recorded in OA LC SLM (optically addressed liquid crystal spatial light modulators). This application, which we have called “the dynamic converter of the distortions’ scale”, is based on the principles of two-wavelength holography, when the hologram is recorded by the radiation at one wavelength, and is reconstructed at another wavelength. If the probe beams, used for the hologram record and reconstruction bear one and the same distortions, one can thus reconstruct the beam, whose distortions are very similar to that of the said probe beams, but their magnitude is scaled down. Such scaling, in turn, can be very helpful in various areas of adaptive optics.

The corresponding results are described in Chapter 1, corresponding to the 1st Interim Report.

On the second stage of the work there was carried out the experimental realization of an interferometer with the dynamic holographic converter. This experiment confirmed the idea and the feasibility of the method, i.e. the applicability of the beam, reconstructed by the dynamic hologram, recorded in OA LC SLM, for the interferometry applications.

The corresponding results are described in Chapter 2, corresponding to the 2nd Interim Report.

On the third stage of the work was carried out fabrication and testing of the LC SLM elements, controlled by visible radiation and controlling the mid-IR radiation. The results of testing are described in Chapter 3, corresponding to the 3rd Interim Report (the investigations in this direction were continued on the 4th stage of work, so the data of the Final report was modified with respect to the 3rd Interim Report).

One the final, 4th stage of work was carried out the experiment on dynamic holographic correction in mid-IR range of spectrum, using dynamic holographic converter of distortions’ scale and the elements, elaborated on previous stages of work. The corresponding results are described in Chapter 4.

1. Dynamic holographic converter of distortions' scale and its applications in adaptive optics

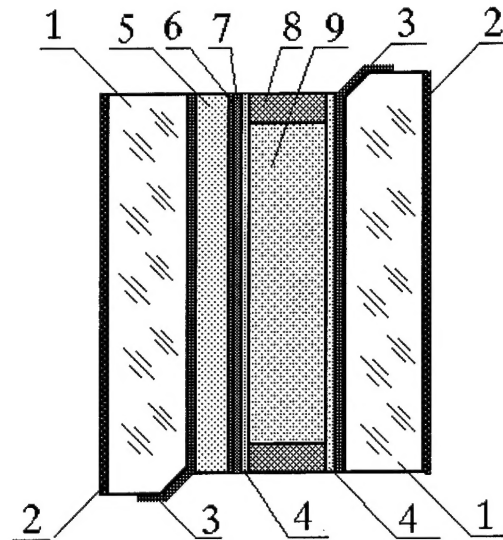


Fig.1. Design of OA LC SLM. In the Figure: 1 – substrata, 2 – AR coatings, 3 – electrodes, 4 – orientation layers, 5 – photoconductor, 6 – light blocking layer, 7 – mirror, 8 – spacers, 9 – liquid crystal.

During the last several years several teams of investigators [1-6], including the contractors, have shown, that the optically addressed liquid crystal spatial light modulators (OA LC SLM) [7], see Fig.1, are very convenient for recording the efficient thin dynamic holograms. Such holograms can be used, in particular, for the dynamic holographic correction of distortions in optical systems, working in the visible range of spectrum, including the systems, working in the incoherent and non-monochrome light. Some of such results were also discussed in the Reports, delivered to EOARD in accordance with the Contract # F61708-96-W0318.

Application of the dynamic holographic correction is important not only for the visible range of spectrum, but also for the ranges with the longer wavelength – near-IR and mid-IR ranges of spectrum. However, the use of OA LC SLM elements for these purposes is prevented by the lack of semiconductors, sensitive for the radiation with the wavelength 1 μm and more, which could have been used as the photosensitive layer (see Fig.1). At the same time it is quite possible to fabricate the LC SLMs, which can address the radiation with the much larger wavelength. It is possible, in particular, to

fabricate the LC elements for the radiation in the band of 1-12 μm , optically addressed by visible radiation [8-12].

In course of this work we have fabricated several specimens of such modulators, which can be used for the record by the visible light of the dynamic gratings (holograms). These holograms were sufficiently efficiently reconstructed by the radiation in the mid-IR range of spectrum. In the experiment was shown the dynamic correction for distortions in the mid-IR range of spectrum, using these elements.

The record of such a dynamic hologram-corrector was carried out in the special optical system, which is also known as the so-called dynamic converter of the wavefront distortions' scale. We have earlier elaborated such a scheme ([13,14], see also the Report for the Contract EOARD #F61708-96-W0309) in conjunction with the studies of the alternative scheme of the nonlinear-optical correction with the use of the so-called negative optical feedback.

The action of such a converter is based on the principles of the so-called dual wavelength holography [15,16], resulting of the following fundamental property of thin holograms. Let us record a thin hologram as the pattern of the interference of the distorted probe wave and non-distorted reference wave. The information about the distortions of the probe wave (on the deviation of its wavefront from that of the reference wave) $\varphi(x,y)$ will be encoded in the hologram as the deformation of its fringes. If one reconstructs such a hologram by the non-distorted wave, the information, encoded in the hologram will be transferred to the wavefront of the reconstructed wave: in some point of the hologram it will be deformed in some value, determined by the deformation of the fringes in this point. The value of the wavefront depletion, measured in terms of radiation wavelength, will correspond to the value of the fringe disposition, measured in terms of grating period. If the wavelength of radiation, used for the hologram reconstruction λ_2 differs from that of radiation, used for the hologram record λ_1 , the shape of deformation of the reconstructed distorted wave $\varphi_2(x,y)$ will be modified with respect to the primary one as $\varphi_2(x,y) = \lambda_2/\lambda_1 \varphi_1(x,y)$. In other words, the use of different wavelengths of radiation on the stages of the hologram record and of its reconstruction provides the tool for scaling of the wavefront distortions.

In the case, when it is necessary to reduce the scale of the distortions many time, it is more convenient to use another scheme of converter. Namely, one can reconstruct the hologram of the distortions $\varphi_1(x,y)$, recorded at the wavelength λ_1 , by the beam with the wavelength λ_2 (and $|\lambda_2-$

$\lambda_1| \ll \lambda_{1,2}$), which bears the same distortions $\varphi_1(x,y)$. In this case there will be reconstructed not the non-distorted reference wave (as it should have been in the case of equal wavelengths of record and reconstruction), but the wave with the residual distortions $\varphi_2(x,y) = (|\lambda_2 - \lambda_1|/\lambda_2)\varphi_1(x,y) = k\varphi_1(x,y)$; $k \ll 1$. In other words, in such case takes place the scaling of distortions with the significant reduce of the scale.

The idea of the dual wavelength holography was first elaborated for the purposes of the holographic interferometry of the large-scale objects [15,16]. In one and the same holographic medium (conventional, i.e. static) there were recorded the holograms of one and the same object at two wavelengths. The spatial beats of these holograms (the moiré pattern) were equivalent to the effective hologram of the same object, recorded at the wavelength, which was many times higher than the wavelengths of the record. The spatial frequency of such quasi-hologram was much smaller than that of usual holograms, recorded in the visible range of spectrum, and thus analysis of the pattern was much simpler.

The results on the technique of dynamic holographic record in OA LC SLM, which we have already mentioned, provide the possibility to implement the discussed principles in various optical schemes, providing the dynamic (real-time) scaling of the distortions of some wavefront. We have said already, that this idea was first proposed by us with respect to the problem of correction of distortions with the use of OA LC SLM in the optical feedback loop [13,14]. The use of the dynamic converter makes it possible to furnish the dual beam interferometer, characterized by the extended range of monotonous variation of output intensity with the growth of the relative phase shift between two branches. In the usual dual-beam interferometer it is equal π , while in our case it equals $n\pi$, here $n = 1/k$.

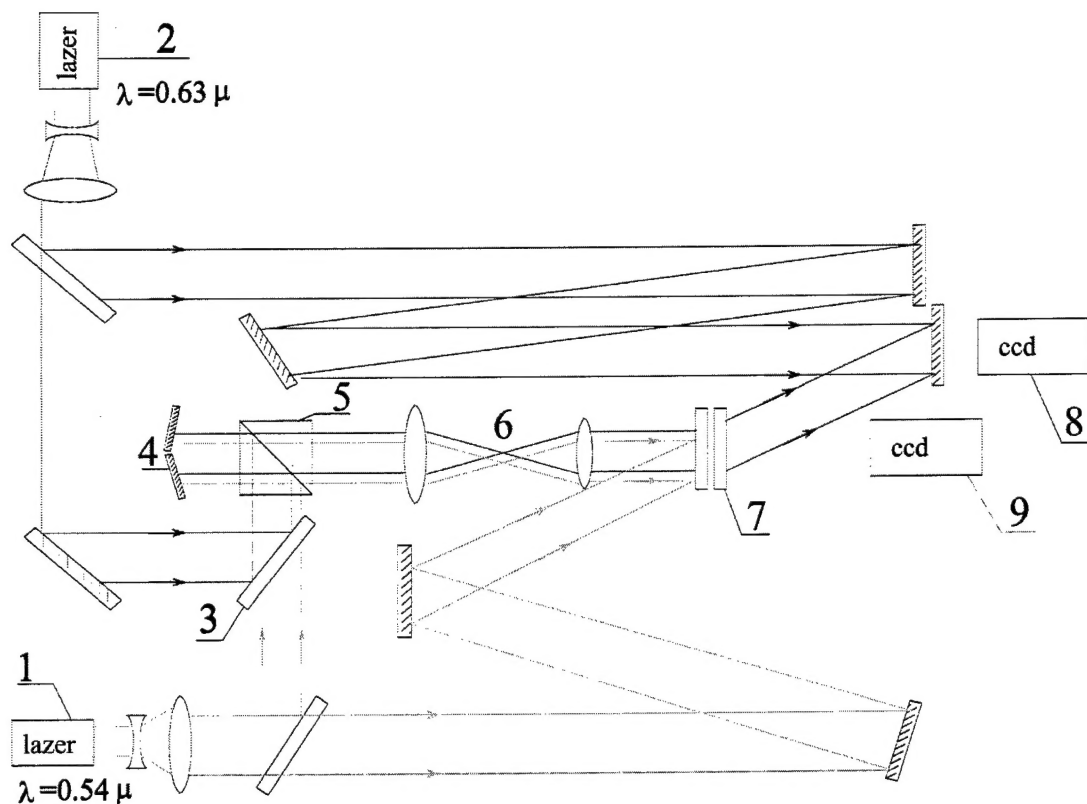


Fig.2. The principle scheme of the setup for studying the principle of holographic converter. In the Figure: 1 - pulsed Nd-laser, emitting at 540 nm, 2 - He-Ne laser, emitting at 633 nm, 3 - dychroic mirror, 4 - model distorter, 5 - beam-splitting cube, 6 - telescope, 7 - OA LC SLM (holographic converter), 8 and 9 - CCD-cameras for registering of the interferograms. The beams at the wavelength 533 nm are shown by green lines, while that on the wavelength 633 nm by the red lines.

In the scope of the reported work we are discussing and analyzing one more application of the dynamic converter. Namely, we suggest to use the dynamic converter for the record of the quasi-hologram of distortions of some optical elements. This quasi-hologram will be equivalent to the imaginary hologram, recorded in mid-IR range of spectrum. Such quasi-hologram can be, in particular, used for the correction of distortions, caused by this element in the same spectral range.

In the scope of this work we have planned to fulfill three separate stages, namely:

Stage 1. Studies of the holographic converter

On this stage we tested in the experiment (as far as we know, for the first time) the dynamic holographic converter of the distortions scale. With this purpose have carried out the following experiment (see scheme in the Fig.2) on the record of the dynamic hologram and its reconstruction at the shifted wavelength. The radiation of the second harmonics of the pulsed Nd laser 1 (wavelength 540

nm) and of He-Ne laser 2 (wavelength 633 nm) is combined by a dichroic mirror 3 into a single beam and is sent to a model aberrator 4 (the set of several mutually tilted mirrors). The reflected beam passes through the beam-splitting cube 5 and telescope 6. The telescope 6 images the model distorter to the plane of the OA LC SLM 7, serving as the holographic converter.

On this stage of work we used the earlier developed OA LC SLM, working in the transparent mode (i.e. lacking the layers 6 and 7 shown in the Fig.1) [17]. In this element is used the polymer photoconductor, which is not sensitive to the radiation of He-Ne laser. That is why the dynamic hologram, recorded by radiation of second harmonics of Nd laser as the pattern of interference of the distorted and non-distorted waves, can be reconstructed by the beam of He-Ne laser radiation without washing out the hologram. Reconstruction of the hologram by the distorted beam of such laser results in partial subtraction of the distortions. The pattern of interference of this wave with differential distortions and of non-distorted plain wave is registered by the CCD-camera 8. CCD-camera 9 is used for registration of the conventional interferogram of the distorter.

In this experiment we have confirmed the feasibility of the dynamic converter concept and tested the applicability of the scaled beam for its consequent use for the record of the dynamic quasi-hologram. (One has, in particular, to provide the sufficient contrast of the corresponding interference pattern; the noise of scattering can be of some problem in this respect etc.).

Stage 2. Fabrication of OA LC SLM for the record of the quasi-hologram - corrector

On this stage we have fabricated and tested several specimens of LC SLMs, addressed by visible radiation and read out by IR-radiation. One can see from Fig.1, that this device has the sandwich-like structure, containing the photoconductor, the light-blocking layer, the reflecting layer (for the work in the mirror-like geometry) and the liquid crystal, positioned between the pair of substrata with the electrodes on their surfaces. In the papers [8,9] were outlined the general concepts of the IR OA LC SLMs. In the papers [10,11] were determined the general approaches to the choice of the working liquid crystal composition and of the working mechanisms, providing the optimal combination of the modulator's parameters, such as reversivity, dynamic range, spatial resolution etc. An example of IR OA LC SLM is described in [12].

Similar to the visible range of spectrum, in the IR-range one can use various electro-optical orientation mechanisms for the phase modulation of radiation in LC SLM [10-12]. In our device we have used the so-called S-effect. It is observed in the homogeneous (parallel orientation) LC-

composition with the positive dielectric anisotropy. Passing through the layer of LC with the thickness d the radiation, polarized along the director, will accumulate the phase delay δ . Its value depends on the distribution of the electric field tension $E(x,y)$ on the surface of the electrode of SLM according to the formula:

$$\delta[E(x,y)] = \frac{2\pi}{\lambda} \Delta n[E(x,y)]d,$$

Here Δn is the value of the optical anisotropy at the wavelength λ .

The utmost reversivity of LC SLM, based on S-effect, is limited by the natural relaxation time τ . The latter depends on the viscosity and elasticity of the medium:

$$\tau \approx d^2 \gamma / \pi K,$$

Here γ is the coefficient of the rotational viscosity and K is the elasticity constant [18].

The design of the OA LC SLM to be fabricated in course of this work for the correction of distortions in mid-IR range of spectrum will be chosen with the account for the following positions:

Substrata. The main problem is to choose the proper material for the substratum, through which the radiation at the wavelength $10 \mu\text{m}$ reads out the recorded grating. Usually for such radiation wavelength are used such media as Ge, ZnSe or some fluorides. The first two media have advantages: high transparency and conductivity, eliminating thus the need to use special electrodes. The disadvantage of these media is the high value of refraction index. It results in strong Fresnel reflexes; Ge, in addition, is oblique for the visible light; the latter circumstance tantalizes the fabrication of the element. The first problem, however, can be solved by use of AR coatings, providing the reduce of the reflection and absorption coefficient down to $<1\%$ and $<0.5\%$ correspondingly. Worth mentioning also, that to prevent the electrochemical processes at the boundary of LC and Ge one has to use special protective coatings, made, for example, of SiO_2 . As to the fluorides of Ba and Ca, the problems are with the presence of the own absorption and due to necessity to use the ITO electrodes ($\text{SnO}_2 + \text{In}_2\text{O}_3$), which also reveal some absorption in the range of $10 \mu\text{m}$. The real transparency of the substratum of BaF_2 with the ITO coating at $10 \mu\text{m}$ equals 70-80%.

Photoconductor. We have used the layer of chalcogenide glass deposited on the substratum of the crystal BaF_2 . This layer has the very high dark conductivity and can be thus easily used with the very thick layer of LC, required for sufficiently high phase modulation in mid-IR range of spectrum. In the

case of choosing the chalcogenide layer the reversivity of the device will be determined by the inertia of this layer and would not thus exceed 3-5 Hz.

LC composition. We have used the nematic composition of the cyanobifenil derivatives, characterized by $\Delta\epsilon \approx 12$, $\Delta n \approx 0.18$ and $T_{N-I} \sim 66^\circ\text{C}$ (the temperature of phase transition from nematic to isotrope phase).

Diffraction efficiency. Literature data on the diffraction efficiency of gratings in OA LC SLMs at $10\ \mu\text{m}$ is unavailable. This range has a special problem, absent in the visible range of spectrum, caused by the absorption at the working wavelength. It results in temporal variation of the birefringence anisotropy and thus of the diffraction efficiency [19]. In evaluation of the expected diffraction efficiency of the grating in IR OA LC SLM one can note the efficiency of self-diffraction, realized at the thermal grating, recorded in LC by the quasi-CW radiation of CO_2 -laser: it was equal $\sim 2\%$ [20].

The Table 1 summarizes the expected parameters of the device which was to be fabricated, evaluated with the account for the above said. For the comparison purposes we give also the parameters of the element, used in the radiometer Inframetric 600 (USA). Similar devices were realized also in Japan and in France.

Table 1.

Parameter	Existing device	Our device
Clear aperture	50 mm	$\sim 35\ \text{mm}$
Spatial resolution	$\sim 20\ \text{lp/mm}$ for the reading-out radiation	
Contrast	At least 1:5	1:5
Transparency	54 %	70 %
Thickness of LC layer	$10\ \mu\text{m}$	$10\text{-}15\ \mu\text{m}$
Reversivity	30 Hz	1-3 Hz

Stage 3. Correction of distortions in mid-IR range of spectrum

In the Fig.3 is shown the principle scheme of the experiment on correction of distortions. In this experiment it is planned to use two lasers, namely the CW Ar^+ -ion laser, emitting at two wavelengths 488 and 514 nm, and the CW CO_2 -laser, emitting at the wavelength of $\sim 10\ \mu\text{m}$. The radiation from both lasers reflects from one and the same model distorter 1; the incidence angles are slightly different, but nearly equal. The beams at all three wavelengths accumulate one and the same distortions. The dichroic mirror splits two spectral components of the Ar^+ -laser. The distorted beam with the

wavelength $\lambda_1=488$ nm interferes with the non-distorted beam with the same wavelength and records thus the holographic converter in OA LC SLM 2.

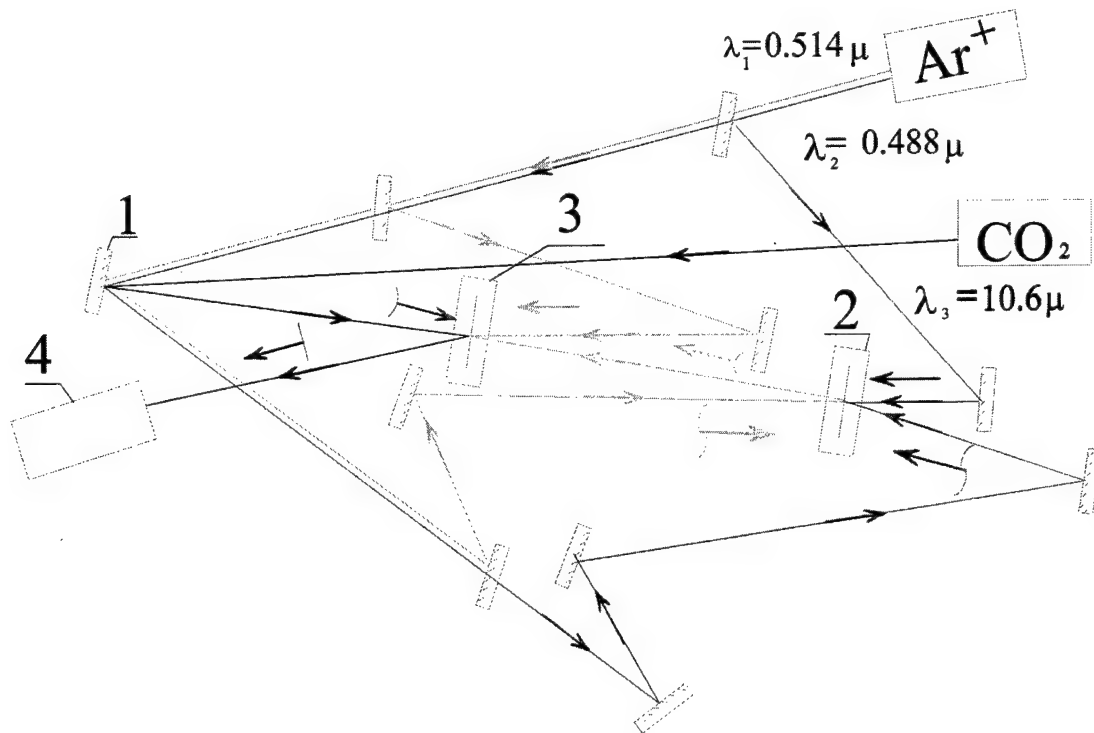


Fig.3. Planned principal scheme of the experiment on the dynamic correction of distortions in mid-IR range of spectrum. In the Figure: 1 - model mirror distorter, 2 - holographic converter, 3 - quasi-hologram - corrector, 4 - system of registration in mid-IR range. The blue lines correspond to propagation of radiation with the wavelength 488 nm, green lines - with the wavelength 514 nm and black lines - to the IR radiation with the wavelength ~ 10.6 μm .

On this stage of the experiment we have planned to use the specially fabricated element with the mirror, separating the channels of hologram record and reading out. The hologram-converter is reconstructed by the distorted beam of radiation with the wavelength $\lambda_2=514$ nm. The diffracted beam has the distortions, reduced in $1/k \approx 20$ times. The interference pattern of such a beam is identical with interference pattern of the beam with the wavelength λ_{opt} , reflected from the same model distorter, with the non-distorted coherent beam. For the said wavelengths of the Ar^+ -laser emission the optimal wavelength equals $\lambda_{\text{opt}}=9.7$ μm . It is rather close to the band of the CO_2 -laser. So we plan to use the "converted" beam with the wavelength 514 nm for the record of the dynamic hologram in the already mentioned IR OA LC SLM element 3. This hologram is to be reconstructed by the distorted beam of the CO_2 -laser. We expected to obtain in one of the diffraction orders the nearly complete correction of

distortions, which is to be observed with the use of special system of registration in the mid-IR range of spectrum 4.

This goal was achieved (see Section 4). However, the failure to fabricate the mirror LC SLM has required to re-configure the setup and to use the transparent element for correction in mid-IR range.

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2. Experimental demonstration of dynamic holographic converter of distortions'; scale

This Section is devoted to the experimental realization of an interferometer with the dynamic holographic converter. The goal of the experiment was to confirm the idea and the feasibility of the method, i.e. the applicability of the beam, reconstructed by the dynamic hologram, recorded in OA LC SLM, for the interferometry applications.

The scheme of the experimental setup is shown in the Fig.4. In this experiment we have tested the holographic scaling of the distortions, imposed by the two-segmented mirror 1 with the relative tilt of its segments. The distortions of this element were read out by the pulsed green radiation of the second harmonics of the Q-switched Nd:YAP laser ($\lambda_1 = 0.54\mu\text{m}$) 2. Its beam was expanded by the 10x-telescope 3 and split by the mirror 4 into the probe and the reference beams. The probe wave passed through the beam-splitting cube 5 and reflected from the two-segmented mirror 1. The reflected radiation has once passed through the cube 5 and through the 2x-telescope, comprised by lenses 6 and 7. In the plane, to which this telescope imaged the mirror 1, was mounted the OA LC SLM 8. Mirrors 9 and 10 sent the reference wave at the wavelength λ_1 to the same plane. The apertures 11($\varnothing 30$ mm) and 12($\varnothing 15$ mm), and the 50%-beamsplitters 4 and 5 provided the equality of the probe and the reference waves' intensities in the plane of OA LC SLM 8.

The dynamic hologram, recorded in SLM 8, was reconstructed by the CW radiation of He-Ne laser ($\lambda_2 = 0.63\mu\text{m}$) 13. The telescope 14 improved its spatial homogeneity. The mirror 15 splits the beam into the probe beam and the reference beam. Optical system, comprised by the lenses 16 and 6 and by the folding mirror 17, sent the probe beam of red light to the same two-component mirror 1. The angles of the green and the red beams incidence to the mirror 1 were very close (difference of 0.02 rad). So the shapes of the distorted wavefronts was practically the same for both probe beams. Red radiation, reflected by mirror 1, was focused by the lens 6, passed aside the mirror 17 and was collected by the lens 7. So it has reached the dynamic hologram, recorded in the OA LC SLM 8. The photoconductor of the OA LC SLM, used in our experiment, was not sensitive to red light of He-Ne laser, so its radiation has only read out the recorded hologram. The reference beam of He-Ne laser radiation passed through the delay line, comprised by the mirrors 18, 19 and 20. This delay line has equalized the lengths of optical paths of the probe and the reference beams with the accuracy of 1 cm.

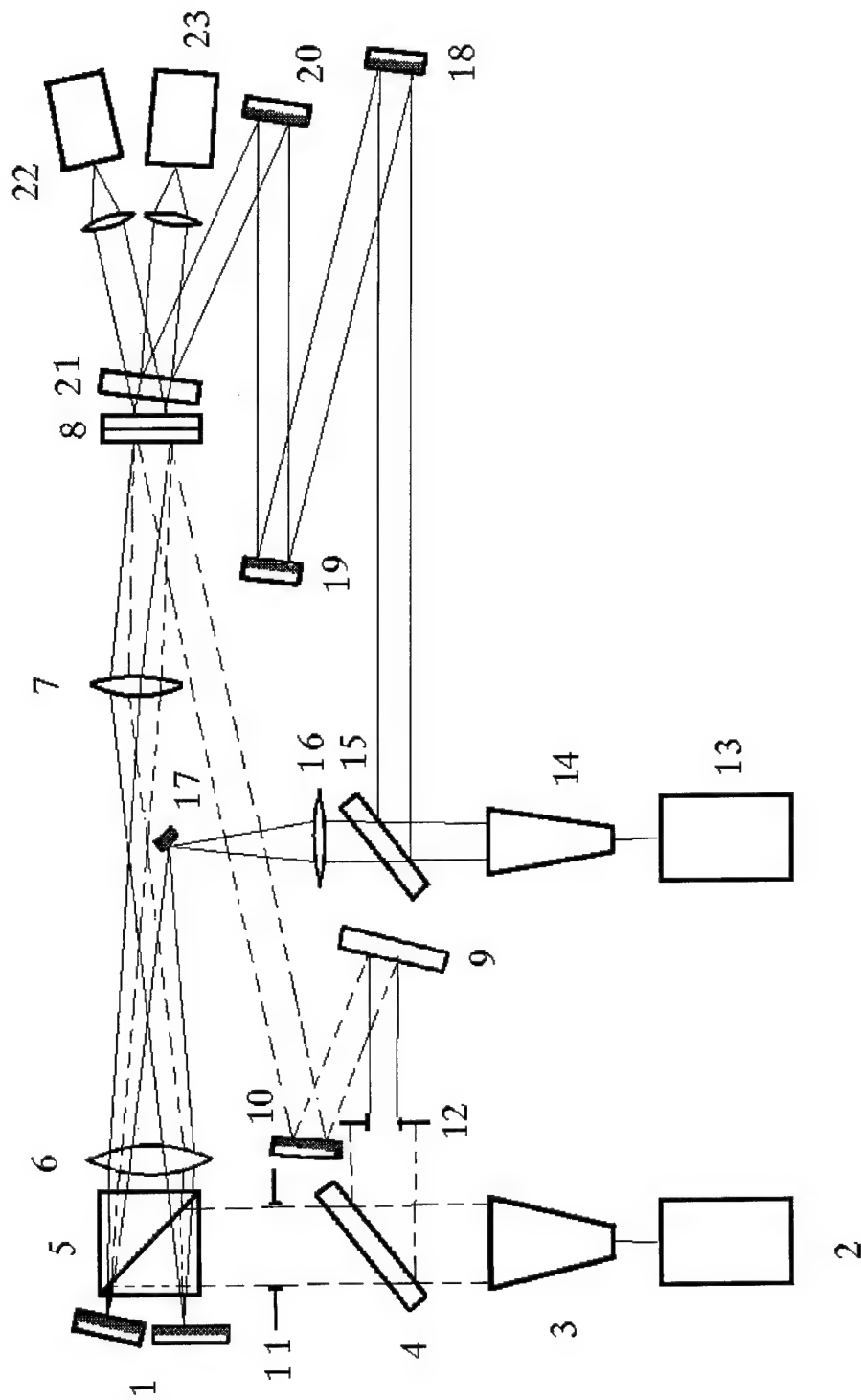


Fig.4. Experimental setup for dynamic holographic converter investigation.
 Nd:YAP laser beams ($\lambda_1=0.54\mu\text{m}$) are shown by the dotted line, He-Ne laser beams are shown by the solid line.

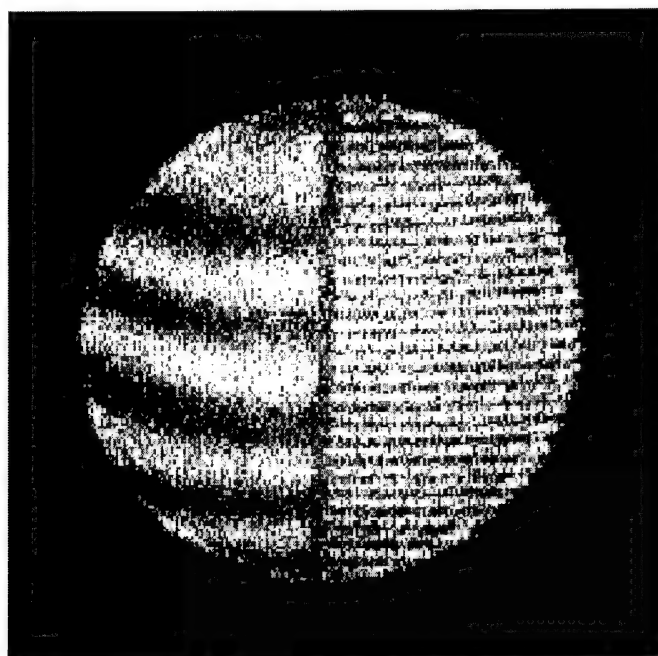


Fig.5. Interferogram of the zero diffraction order beam

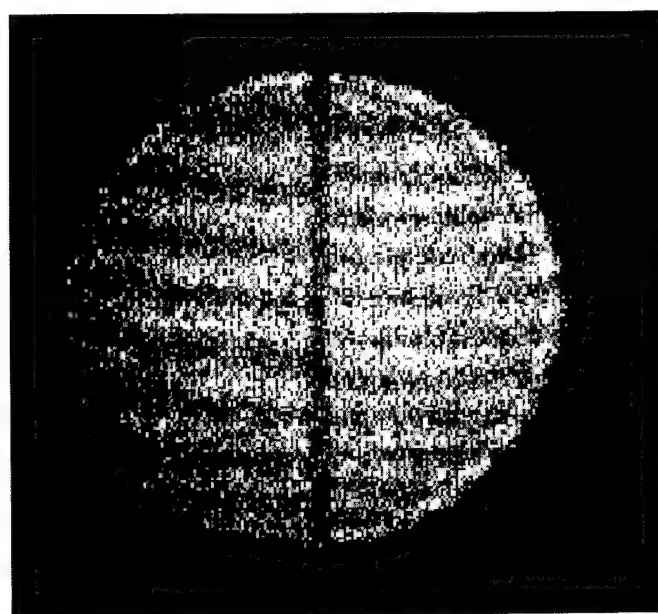


Fig.6. Interferogram of the first diffraction order beam

The semitransparent mirror 21 reflected the reference beam of He-Ne laser. This mirror and the mirror 20 had two positions, providing registration of the interference pattern of the reference beam either with the beam of the first order of diffraction (CCD-camera 22) or with the beam of the zero order of diffraction (CCD-camera 23). So we had the possibility to register the interferogram of the probe beam, distorted by the mirror 1, and of the beam with scaled down distortions.

In the Fig.5 is shown the interferogram of the beam, going to the zero order of diffraction, i.e. just the interferogram of the two-segmented mirror. In the Fig.6 is shown the interferogram of the beam, going to the first order of diffraction. One can see the pretty good quality of these interferograms. Both interferograms correspond to the beams with the relative tilt around the horizontal axis. Comparing the right and the left sides of each interferogram, one can evaluate this relative tilt. The processing of two interferograms and comparison of the results has shown that the distortions magnitude was reduced 5.8 times, what well corresponds to the above given relationships.

In conclusion we can say, that we have realized in the experiment the scaling of the distortions of the coherent radiation wavefront. The wave with the reduced distortions was obtained by means of reading out by the distorted probe wave of the dynamic hologram in optically addressed liquid crystal spatial light modulator, recorded at another wavelength by the probe wave with the same distortions. The scaling rate, which was measured in the experiment, well correlates with the theory. This technique of distortions' scaling can be useful for various applications in the adaptive optics, in particular, for:

- recording of the dynamic holographic correctors, working in spectral ranges, where laser sources for holographic record are unavailable, in particular, in mid-IR range of spectrum;
- extension of the range of distortions, which can be corrected by means of the phase valve, mounted in the negative optical feedback loop;
- simplification of the procedure of the measuring of the robust wavefront distortions.

3. LC SLMs for dynamic holography in mid-IR, addressed by visible light

The key element for the record of the differential (two-wavelength) dynamic holography for correction in mid-IR is an LC SLM element of special design, addressed by visible light, but read-out by mid-IR radiation. The development of such elements is an independent task, interesting not only from the point of view of two-wavelength differential dynamic holography. During the recent time there were discussed various schemes, where the record of dynamic hologram in LC SLM is split into several stages. On the first stage the interference pattern is registered by some matrix. of photosensors. Then it can be processed, - for example, with the purpose of its sharpening (blazing) so as to increase the diffraction efficiency of the resulting hologram [2]. Then the hologram is transferred to the LC SLM. Such transfer can be done by means of image transfer. One can, in particular, apply this multi-stage scheme for mid-IR correction, if he has the matrix of photosensors, sensitive to IR radiation; the processed interference pattern can be restored in visible light and thus transferred to OA LC SLM of the kind under consideration.

To the best of our knowledge, before we have started our work, nobody has developed the elements of such a kind for the dynamic holographic registration, and thus our results are to a large extent a pioneering ones. We have developed, fabricated and tested more than 10 such devices. With their use we have demonstrated the feasibility of the scheme of the two-wavelength dynamic differential holographic correction in mid-IR range of spectrum nearby 10 μm (see Section 4). On the base of this preliminary experience we have also formulated the proposals on further development of the corresponding technology.

Design of elements

The standard design of OA LC SLM is shown in the Fig.1 (see Section 1). The standard glass substrata were in our case replaced by the substrata, made of BaF_2 with the thickness of 3 mm so as to provide the reading out in mid-IR; no AR coating was used. The elements were designed and tested for nearly normal incidence. Provision of the sufficiently high diffraction efficiency at 10 μm requires the use of rather thick LC layer, whose thickness varied from 10 to 15 and even 20 μm in various specimens.

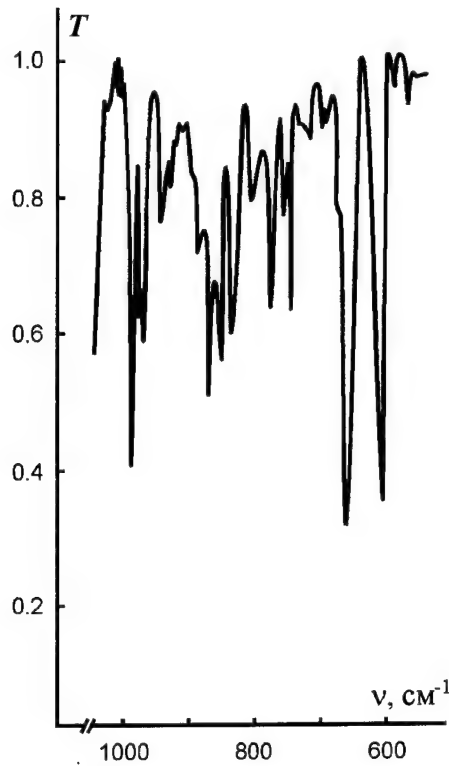


Fig.7. Spectrum of LC composition transmission

First it was planned to use the elements with the mosaic metallic mirror, separating LC layer and photoconductor layer. We have fabricated two LC SLM element with mirror (i.e. working in the reflection mode), made of Al with the transverse size of single mosaic pixel $30\text{ }\mu\text{m}$ and period $40\text{ }\mu\text{m}$. We have supposed that, due to the large wavelength of reading out radiation, the scattering on the mosaic elements will be within the admissible level. However, these hopes have failed and further all the elements have had the transparent geometry..

Optical quality of substrata (BaF_2 , thickness 3 mm) was $N=1$; $\Delta N=1$; $P=IV$; $Q\sim 30''$.

The chalcogenide glass layer with the thickness of $1\text{ }\mu\text{m}$ (specific conductivity $10^{-13}\text{ }\Omega\text{ cm}^{-1}$) served as the photoconductor layer. The choice of this medium was determined by its very high dark resistance, simplifying the electric coupling of this layer with the thick layer of LC [2]. This medium is transparent for radiation at $10\text{ }\mu\text{m}$. The layer sensitivity to the recording wavelength of $\sim 530\text{ nm}$ is approximately $\sim 10^{-5}\text{ W/cm}^2$. Very high sensitivity of chalcogenide layer imposes some difficulties, caused by the necessity to protect it from daylight.

Electrical conductivity was provided by the standard ITO layer. This layer strongly absorbs radiation with the wavelength 10 μm . That is why we have fabricated series of elements with the different thickness of ITO layer. Depending upon it, the total transparency of the overall LC SLM element varied from 5-6% to 60-70%. The elements with the different thickness of ITO layer did not reveal some specific features in their behavior, and thus one can treat the problem of absorption in ITO layer as the solved.

The element performance was based on the S-effect in nematic liquid crystal. The primary planar structure of LC was produced by means of the inclined deposition of the orientation layer of GeO. The LC-composition was chosen with an account for two requirements. First, it had to provide the sufficiently high birefringence in mid-IR range. The birefringence of the used composition was $\Delta\varepsilon=12$ and $\Delta n=n_{\parallel}-n_{\perp}=0.18$ at the wavelength of 10.6 μm , $T_{NI} \sim 64^{\circ}\text{C}$. Another requirement was the absence of the absorption peak at the working wavelength. In the Fig.7 is shown the absorption spectrum of this LC composition in the range nearby 10 μm . At the working wavelength its absorption is equal $\sim 30 \text{ cm}^{-1}$.

The Table 1 contains the physical parameters of SLM components. Here d is the thickness of the layer, α is the radiation absorption coefficient, κ is the thermal conductivity coefficient, c is the thermal capacity, ρ is density and n is the refraction index.

Table 1. Parameters of SLM components

	Medium		
	BaF ₂	ITO	LC
$d, \mu\text{m}$	3×10^3	0.5	20
α, cm^{-1}	0.3	3.4×10^3	30
$\kappa, \text{J/cm sec degree}$	0.07	0.12	0.05
$c, \text{J/g degree}$	0.6	0.38	0.5
$\rho, \text{g/cm}^3$	4.83	6.95	0.8
n	1.4÷1.45	2	1.6

Best results were observed for feeding the element by the repetitive negative voltage (within the range of 6-20 V) pulses with the duty cycle 1:1. Chalkogenide layer is rather slow, so for the repetition rates over 1 Hz the diffraction efficiency

becomes smaller.

The testing in the optical addressing mode was preceded by testing the elements in the mode of electrical controlling. The modulator was mounted in the beam of He-Ne laser between two crossed polarizers. It was fed by the arbitrary voltage pulses, and the number of He-Ne laser radiation oscillations was counted. For various specimens it varied from 2.5 to 5, indicating the electrically induced phase retardation of up to 5λ , i.e. more than $3\text{ }\mu\text{m}$. Our previous experience indicates that in the mode of optical addressing the maximal available phase retardation is some 0.6-0.7 of its value, produced by the direct electric control, i.e. some $2\text{-}2.5\text{ }\mu\text{m}$ in our case. This results well correlates with our previous results [2], when we have observed the optically induced phase retardation of He-Ne laser radiation of more than $2\text{ }\mu\text{m}$ in the modulator, comprised by the same chalcogenide photoconductor layer and by LC layer with the thickness $20\text{ }\mu\text{m}$, but mounted on the glass substrata.

Thermal parameters of SLMs

We have said already (see Section 1), that one of the main difficulties in fabrication of the LC elements for the mid-IR range of spectrum is the inevitable absorption of radiation in LC medium due to its own absorption. Some of possible applications of such elements deal with laser radiation, so it is important to understand the possible thermal regime in the element. We have carried out some calculations so as to evaluate influence of possible heating onto the most important parameter of the LC medium – its birefringence. The value of the refraction index anisotropy Δn determines the dynamic range of phase modulation in LC device, based on S-effect. At the same time, this value is very sensitive to the medium temperature. The coefficient of thermal nonlinearity dn/dT can be as high as 10^{-3} , and nearby the phase transition its value can reach some 10^{-2} . In the Fig.8 is shown the dependence of Δn at the wavelength of $10.6\text{ }\mu\text{m}$ vs. temperature for the composition, which we have used in our elements. One can see from this dependence that the temperature range, where the LC modulator does not need thermal stabilization is positioned nearby the room temperature and can not exceed 28°C . The physical properties of the modulator components are well known, and the theory of heat transfer makes it possible to model with the sufficient accuracy the thermal processes in the modulator. So one can evaluate the temperature dynamics in the

modulator. Such an evaluation was done.

Assume that the SLM controls the radiation of CW CO₂-laser with the power of 1 W in the beam with the diameter 1 cm. Let us neglect the reflection from media boundaries and thus evaluate the absorption in different value. The heat deposition can be evaluated according to the standard Buger-Lambert law: $W = W_0(1 - e^{-\alpha \Delta x})$. The results of calculations are summarized in the Table 2:

Table 2. Absorption in modulator layers.

Layer	BaF ₂ (1)	ITO (1)	LC	ITO (2)	BaF ₂ (2)
Absorbed power, %	13	24	6.5	2.5	1

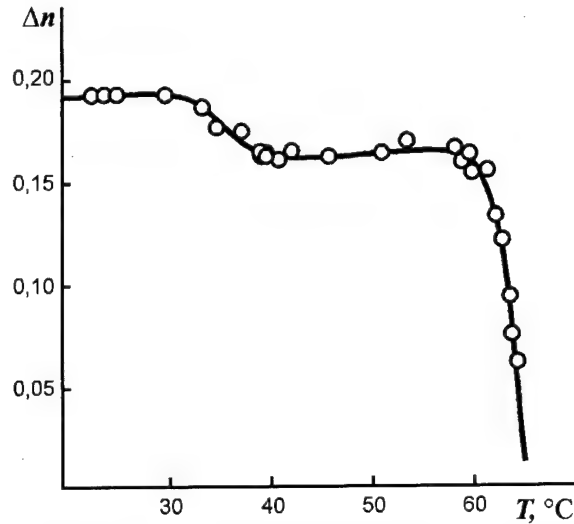


Fig.8. Thermal dependence of birefringence Δn of LC composition at 10.6 μm

So, according to the evaluations the modulator absorbs $\sim 47\%$ of the total incident power or ~ 0.5 W, and the most of this energy is absorbed in the internal layers of the element. The thickness of these layers is very small and thus in calculation of heat sink one can neglect the time, which is required for establishing of the thermal equilibrium between the layers. The absorption in the substrata is negligible, and thus the thermal conductivity equation without the internal sources of heat, which looks like:

$$\frac{dT}{dt} = a^2 \frac{\partial^2 T}{\partial x^2} \quad (1)$$

makes it possible to introduce the characteristic time of thermal transfer in the practically non-absorbing layer $\tau = (\Delta x)^2 / a^2$, where a is the thermal conductivity

coefficient ($a^2 = \kappa/c\rho$). During this time, the temperature on the second edge becomes “significantly” different with the one on the first edge of the layer. I.e., this time determines the time of heat transfer through the layer. So the absorbed heat is equal to $Q = W\tau = cm\Delta T$. Thus, the value of $\Delta T = W\tau/c\rho V$ determines the growth of the temperature of the layer during the time τ . For the BaF₂ substrata, this time is equal 4 seconds, and they will be heated in 2°C. Such heating can not vary the modulator’s parameters, so one can analyze the stationary mode. In this case, the difference of temperature values ΔT at the layer boundaries can be determined from the relationship $\Delta T = \Delta x W / \kappa S$, where S is the double square of the layer. For BaF₂ $\Delta T = 1.5^\circ\text{C}$.

One can see that the evaluation of temperature difference at the edges of the BaF₂ plate coincides with the value of its heating during heat transfer via thermal conductivity. Taking into account, that the heat will be transferred also through the layer of Si (it has higher thermal conductivity) and that the heat will be transferred through the BaF₂ plate also in transverse direction, one can treat the given value as the highest value of possible heating. So one can preserve the working temperature in the appropriate range of 20..28°C just by means of passive heat sink from the external surfaces of BaF₂ substrata by means of, for example, massive metallic apertures.

One can also carry out the similar calculations and to evaluate the maximal possible power loading of the SLM with the discussed design. For $\lambda = 10.6 \mu\text{m}$ it equals $\sim 4\div 5 \text{ W/cm}^2$. For the higher power fluency and without the active heat sink the thermal nonlinearity processes will dominate the required electro-optical effects.

Measurement of spatial resolution (optical)

Optical (non-holographic) resolution of SLM elements was measured according to the projective methodic (see the measurement scheme in the Fig.9). The test-chart 2 was imaged by the lens 3 in the visible light of the source 1 to the photosensitive layer of the modulator. This image was reconstructed by the IR-radiation black body source 5, emitting in the range of temperature $t_{room} + (2\div 20^\circ\text{C})$. The image was visualized by the thermal vision system 9. The resolution of this system was limited by the value of $5\text{-}6 \text{ mm}^{-1}$, and it was found out that the resolution of our elements was better than the said value (see Fig.10).

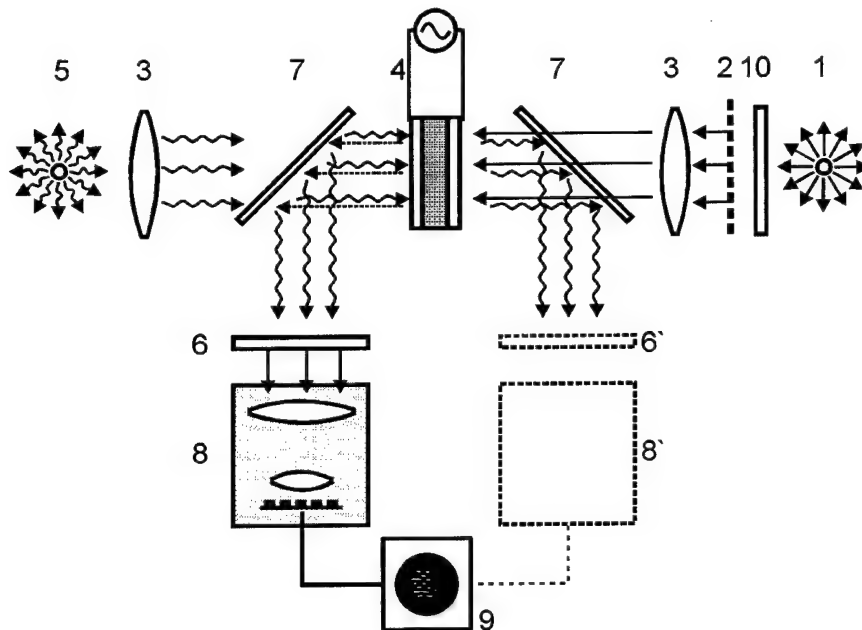


Fig.9. Measurement of optical resolution of SLM. In the Figure:
 1 – visible light source, 2 – test-chart, 3 – lens, 4 – SLM, 5 – “black body”
 thermal source of IR radiation, 6 – polarizer-analyzer, 7 – semitransparent
 mirror, 8 – lens of thermal vision system, 9 – thermal vision system, 10 –
 filter.

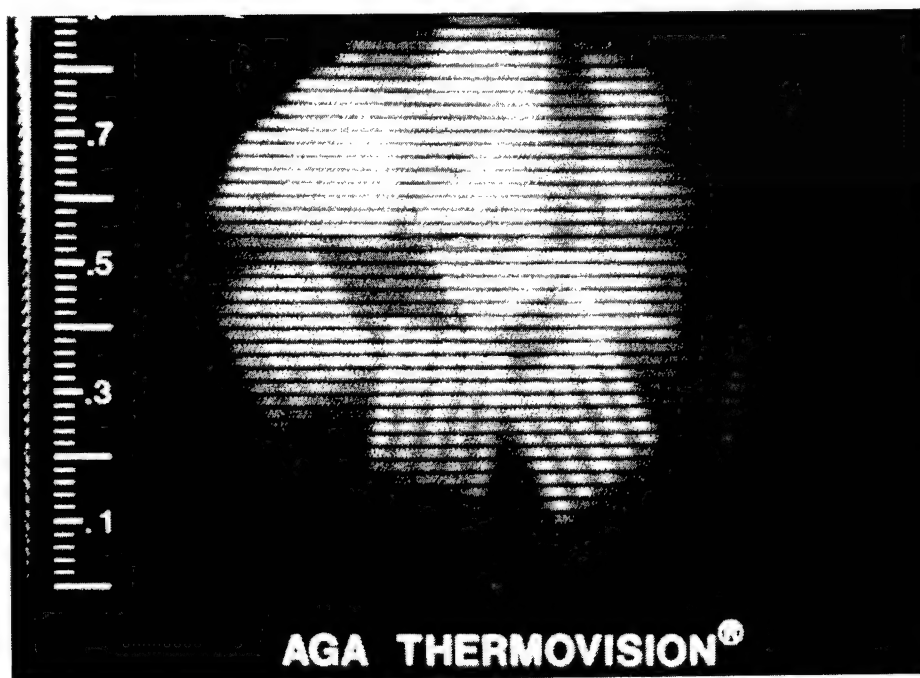


Fig.10. Thermal vision image in IR light of test-chart, recorded by visible light in
 modulator

Homogeneity of phase response

In the IR range of spectrum the influence of element defects onto the controlled beam quality is much smaller than in the visible range due to the much larger wavelength, so we have had the opportunity to test the homogeneity of the phase grating, recorded in SLM, with the use of visible radiation of single mode He-Ne laser. All the surface of the photoconductor layer was illuminated by the periodical structure with the period $\Lambda=25\text{ }\mu\text{m}$. All the surface was step-by-step discretely scanned by He-Ne laser beam with the diameter 3 mm. Ratio of intensity in the first and zero orders of diffraction was measured for each position of the beam (Fig.5). It was found out that the diffraction was observed across the overall surface of modulator, and the variation of the measured diffraction efficiency did not exceed 10%.

Measurements of diffraction efficiency

Diffraction efficiency of elements in the mid-IR range was measured with the use of single mode CW CO₂-laser, emitting at $10.6\text{ }\mu\text{m}$. The scheme of measurements is shown in the Fig.11. The grating was recorded by the visible light as the image of the periodical chart. Variation of this image scale provided variation of the grating period within the range of $5\div 20\text{ mm}^{-1}$. The diameter of CO₂-beam was equal 3 mm, and its power $\sim 100\text{ mW}$. Diffraction pattern was registered by two means:

- 1) Visualization at the screen of thermal vision system, sensitive in the mid-IR range of spectrum. In this case one could observe the whole pattern, but only evaluate the diffraction efficiency. This evaluation was done by means of approximate equalizing of the intensities in the zero and first diffraction orders by means of absorbing filters (see Fig.12)
- 2) Absolute measurements were carried out with the use of pyroelectric sensor MG-30. The diffraction efficiency was measured as the ratio of the first diffraction order energy to that of the total beam after passing through the modulator (i.e. without account for radiation absorption). It was found out that for various elements it varied within the range 1.5-5% of the total energy transmitted through SLM, for all checked spatial frequencies of the grating. Such variation did not reveal any regularity; the elements with very close design could reveal rather different values of diffraction efficiency. They could also vary with time (it may be caused by room temperature variations and by aging factor.

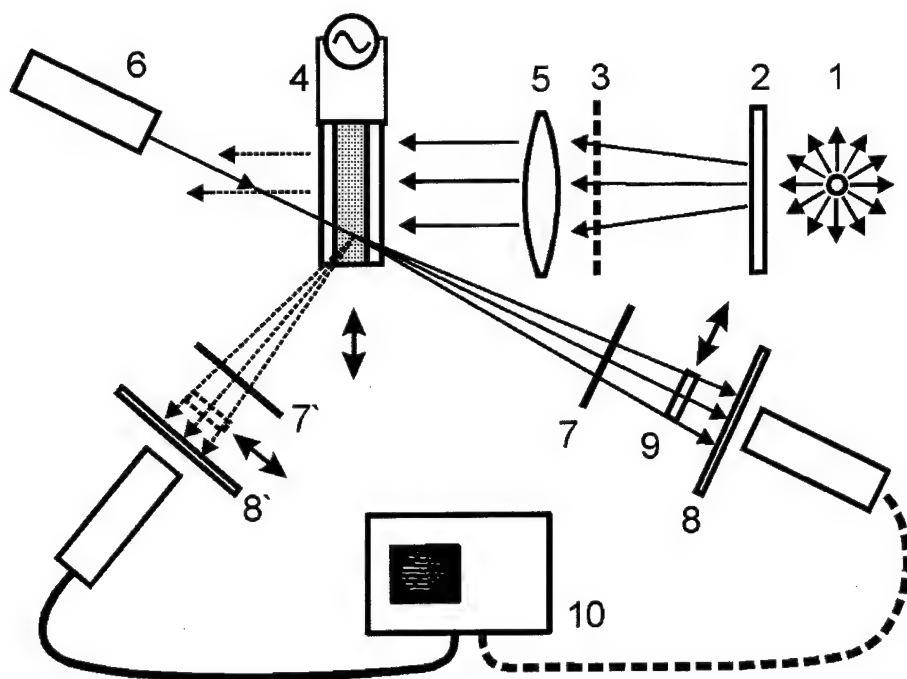


Fig.11. Scheme of measuring of intensity of diffraction orders. 1 – source of visible light, 2 – filter, 3 – test-chart (grating with $\Lambda=25\text{ }\mu\text{m}$), 4 – SLM, 5 – lens, 6 – laser source, 7 – polarizer-analyzer, 8 – screen, (positions 7', 8' were used for measurements of SLMs with mirror), 9 – attenuators, 10 thermal vision system or oscilloscope with pyrosensor

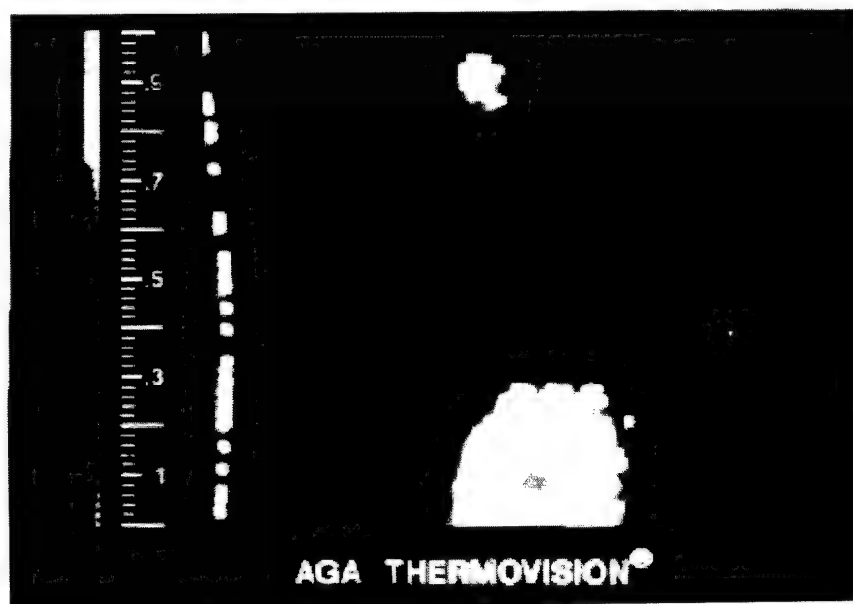


Fig.12. Image of zero (bottom) and first diffraction orders of CO_2 -laser radiation registered by thermal vision system

Conclusions

1. We have developed and fabricated the transmitting LC SLM elements for the record of dynamic holograms, addressed by visible radiation and reconstructed by mid-IR range radiation. The elements are based on the use of chalcogenide photoconductor and of the thick (up to 20 μm) thick layers of special nematic LC composition, which reveals weak absorption ($\sim 30 \text{ cm}^{-1}$) at the working wavelength (10.6 μm) and high birefringence ($\Delta n \sim 0.18$). The depth of phase modulation (retardation) in such elements can be as high as 2 μm and more.
2. We have shown the admissible (2-5%) value of diffraction efficiency from dynamic gratings with the spatial frequency $5 \div 20 \text{ mm}^{-1}$, recorded in such elements. It made it possible to fulfill an experiment on dynamic holographic correction of optical distortions in mid-IR range of spectrum (see Section 4).
3. The technology of fabrication of OA LC SLMs of the novel type is yet incompletely developed and mastered, and it requires further development. The fabricated pioneering specimens reveal yet some instability and irreproducibility of their parameters, caused by the large thickness of LC layer, by the incomprehensive technology of deposition of secondary layers (transparent electrode and orientation layer) onto the crystalline substratum. On the base of accumulated experience we have formulated the proposals on further development of the technology of OA LC SLMs for mid-IR holography.

Proposals of development of OA LC SLMs for dynamic holography in the range of 3-5 μm

Recent years has shown fast progress in development of technique of compensation for distortions in laser and imaging optical systems, working in the visible spectral range, with the use of dynamic holographic record in optically addressed liquid crystal spatial light modulators (OA LC SLM). However, the use of similar technique in the very important mid-IR range of spectrum is tantalized by lack of photoconductors (key element of OA LC SLM), sensitive to mid-IR radiation.

Nevertheless, recently there were shown several opportunities to realize the dynamic holographic correction in mid-IR with the use of LC SLM elements, controlling mid-IR radiation, but addressed by visible light. One of such techniques is

based on dual wavelength dynamic holography, when the holographic corrector for mid-IR is recorded with the use of two visible wavelengths as the quasi-hologram at differential wavelength. One can also register the interference pattern by matrix of photosensors (and such matrices are available not only in visible, but also in mid-IR range) and then reconstruct it in visible light. The latter technique is especially interesting due to the possibility of special processing of interference pattern, when the symmetrical profile of interference fringe is substituted by the wedge-like asymmetric pattern. Restored in LC SLM as the phase retardation profile (in this case one has to use the elements providing the gray scale phase retardation within the limits of one wavelength of controlled radiation) it produces the so-called "blazed" hologram, characterized by very high diffraction efficiency.

In this case one needs to use the elements with rather large (in comparison with traditional elements for visible light) thickness of LC layer. Provision of phase retardation of ~ 2 PI or at least of the sufficiently high diffraction efficiency requires that this thickness should be at least 20-30 microns. It will inevitably result in aggravation of spatial resolution and reduce of SLM reversivity

We suggest solving this problem in the following manner. In usual OA LC SLM elements the mirror layer is placed between the layers of LC and of photoconductor so as to protect the photoconductor from the action of controlled radiation. However, in our case it is not important because mid-IR radiation does not influence onto photoconductor. So one can position LC and photoconductor layers from one and the same side of the mirror. In this case, one has to fulfill two requirements:

- the photoconductor layer is to be transparent for reading-out mid-IR radiation;
- the mirror, reflecting the mid-IR radiation, has to be sufficiently transparent for the visible light, recording the hologram.

Both requirements can be fulfilled rather easily. We suggest to fabricate several elements of such a kind and to test them. It is supposed that there will be fabricated the elements on the base of nematic LC, applicable for dynamic holography in the practically important spectral range of 3-4 microns. We also suggest fabricating the elements, proving the gray scale phase modulation within the range of at least one wavelength (2 PI) in the range of 3-4 microns, applicable for blazed holography in this spectral range.

The elements of the said design are also very convenient for experimental

evaluation of one novel concept of OA LC SLM design, promising significant increase of diffraction efficiency. If one has two sequential transmission diffraction gratings, and the reading-out radiation diffracts on two gratings sequentially, under specific conditions the diffraction to the useful orders from both gratings can be coherently coupled, providing thus significant growth of the overall diffraction efficiency to the useful diffraction order. The characteristic scale of such effects along the optical axis is determined by the ratio of the square of dynamic grating period to the wavelength of reading out radiation, i.e. is equal to $\sim 1\text{mm}$ or less. The described design of the LC SLM element, addressed by visible radiation and read-out by mid-IR radiation is especially convenient for testing and evaluation of the described concept, because one can just introduce the additional spacer layer of the necessary thickness between the mirror and LC layer.

The goal of this work is to fabricate LC SLM elements with the mirror geometry, addressed by visible radiation and addressing mid-IR radiation (3-4 microns). The elements are to provide the high net optical efficiency for the record of dynamic gratings and the possibility to record the phase gratings with the amplitude of phase retardation of up to 2 PI in the said spectral range.

It is proposed to carry out two stages of the work.

On the first stage it is planned to solve the following tasks:

- to optimize the parameters of the mirror, photoconductor and nematic LC so as to provide the high diffraction efficiency;
- to minimize light losses on the boundaries of the media, comprising the SLM;
- to test the parameters of SLMs and to deliver two specimens to the Customer.

On the second stage it is planned to solve the following tasks:

- to investigate the possibility of diffraction efficiency improvement by means of choosing the optimal distance between the mirror and LC layer;
- to test the parameters of SLMs and to deliver one specimen to the Customer.

Technical parameters of SLMs to be developed

clear aperture	20 mm
optical quality	at least quarter wave
geometry of SLM	with mirror
wavelength of record	0.5-0.7 micron
reading out wavelength	3-4 microns

spatial resolution	10-20 lp/mm
net optical efficiency	
1 st stage	10-20%
2 nd stage	> 30%,
phase retardation	up to 2 PI at 3-4 microns

References for Section 3

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2. V.Yu.Venediktov, V.A.Berenberg, N.A.Bezina et al. Proc.of SPIE, **3684** (1998) 45.

4. Experiment on dynamic holographic correction for distortions in mid-IR range of spectrum

The principle of dynamic holographic correction of optical distortions by means of differential two-wavelength dynamic hologram in OA LC SLM was tested in experiment, using the developed principles and devices. The failure to fabricate the mirror-like LC SLM for mid-IR, addressed by visible radiation, has required to modify the scheme of this experiment (see Fig.3, Section 1) so as to use the transparent element.

In the Fig.13 is shown the scheme of the experimental setup. Model distortions to be corrected were imposed by the two-segment mirror 11. The mid-IR radiation with the wavelength $10.6\text{ }\mu\text{m}$ was provided by CW CO_2 -laser 31. The record of dynamic holographic converter of distortions' scale (see Section 2) and of the differential dynamic hologram of distortions was provided by radiation of multi-frequency CW Ar-ion laser 1. The most intense lines of Ar laser spectrum have the wavelengths 488 nm (further referred to as "blue") and 514 nm (further referred to as "green"). As it was shown in Section 1, their use in the scheme of dynamic holographic converter provides the record of the differential hologram, corresponding to the optimal correction wavelength $\Lambda_{\text{eff}} \approx 9.7\text{ }\mu\text{m}$, which is rather close to standard wavelength of CO_2 -laser $10.6\text{ }\mu\text{m}$. Extraction of these lines out of the whole spectrum of Ar-ion laser emission and their mutual separation was done by reflective diffraction gratings 3 and 13.

Radiation of Ar-ion laser 1 was collimated by telescope 2. The diffraction grating 3 expanded it to several diffraction orders. The beams, going to the first diffraction order was used as the plain reference waves for the record of dynamic holograms. The beam, going to the zero diffraction order, was then reflected by the two-segment mirror 11, thus reading out its distortions.

Nondistorted plain beams of the first diffraction order were thus spatially separated. The plain wave of green light was reflected by the mirrors 4 and 5, spectrally cleaned by the filter 30, passed through delay line (mirrors 6,7,8) and through beam-splitting cube 9 and reached the OA LC SLM 10. The plain wave of blue light was reflected by mirrors 4 and 17.

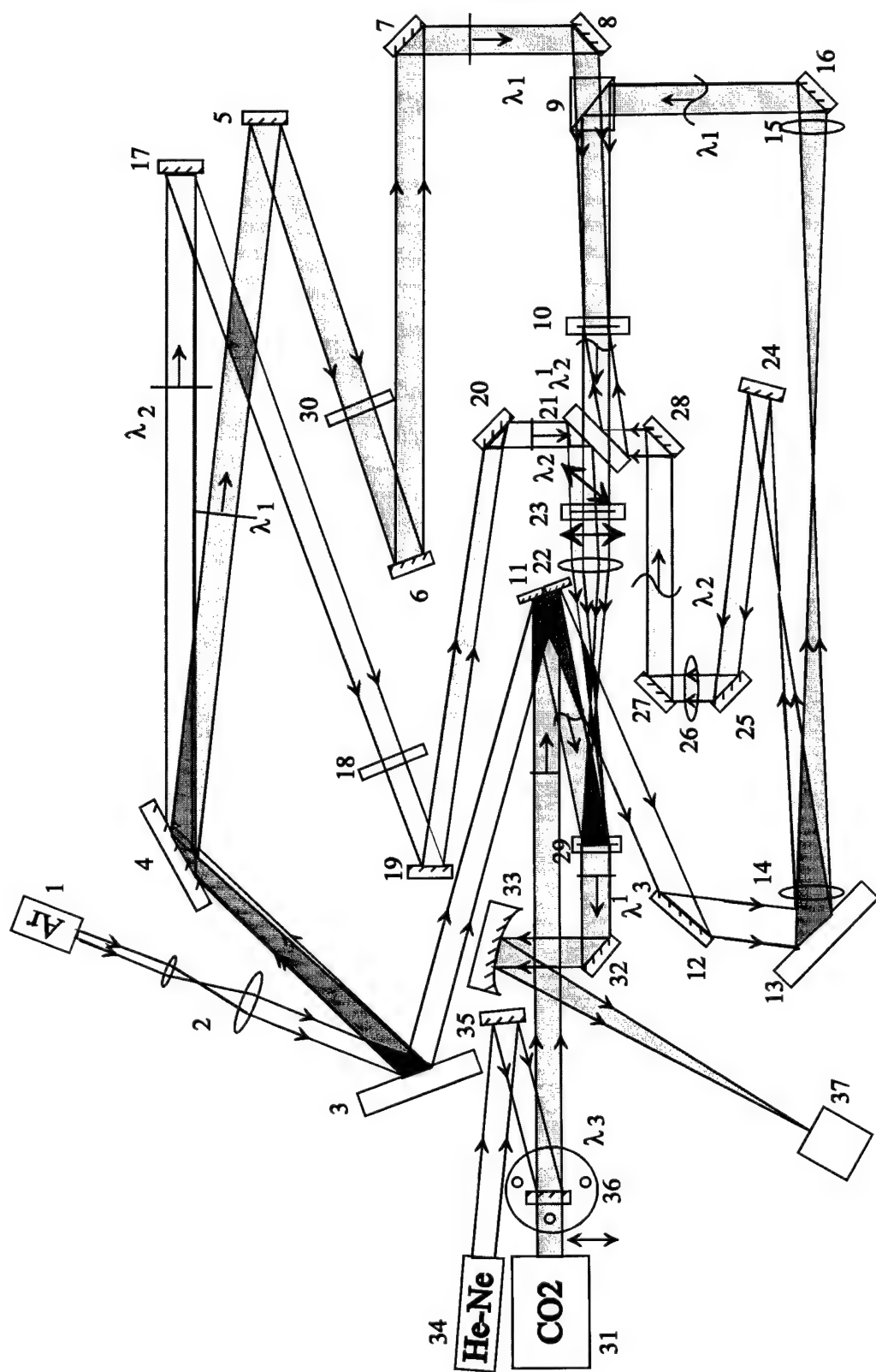


Fig.13. Experimental setup for dynamic holographic correction in mid-IR range of spectrum

Collinear zero diffraction order green and blue beams, distorted by mirror 11, were reflected by mirror 12 and then spectrally separated by the diffraction grating 13. The distorted beam of green light passed through the lenses 14 and 15, through beam splitting cube 9 and reached the SLM 10. Mutual angle between non-distorted reference wave and distorted probe wave of green light at the SLM was 2.5×10^{-2} . Lenses 14 and 15 imaged the pupil of mirror 11 to photoconductor layer of SLM 10, recording thus the dynamic hologram of mirror 11 distortions with the spatial carrier of 50 lp/mm.

We have used the ferroelectric OA LC SLM 10 with the mirror-like geometry as the element for the record of the dynamic holographic converter of distortions' scale. The hologram, recorded in this element was read out by the distorted wave of blue light. This beam after reflection from the distorted mirror 11 and diffraction on the grating 13 passed through the lens 14, was reflected by the mirrors 24 and 25, then passed through the lens 26, was reflected by mirrors 27 and 28 and by beam-splitter 21 and, at last reached the SLM 10. The lenses 14 and 26 were imaging the pupil of the mirror 11 to the SLM 10.

The blue radiation was diffracting on the dynamic hologram 10, forming thus the wave with the scaled down distortions. This wave was sent to the IR LC SLM 29, addressed by visible light. Lens 22 was imaging the pupil of hologram 10 to the photoconductor layer of LC SLM 29.

We have used one of transparent nematic LC SLMs of special design (see Section 3) as an element 29. Here was recorded the dynamic hologram as the interference pattern of two blue waves: one above said probe wave with the scaled down distortions and another plain wave (reference). This reference wave was produced by diffraction of the primary laser radiation at the grating 3 to the first order of diffraction. The diffracted beam was reflected by mirrors 4, 17 and 19, its intensity was equalized with the probe wave by filter 18, then it was reflected by the beam-splitter 21, passed through the lens 22 and through the shutter 23 to the SLM 29. Here was recorded the dynamic hologram with the spatial carrier frequency 10 lp/mm, which served as the corrector for distortions of the mirror 11 in IR range.

The radiation of CW CO₂-laser 31 was distorted by the mirror 11 and entered the dynamic hologram – corrector 29. Zero or first diffraction orders of IR-radiation from the hologram were reflected by copper mirror 32 and focused by spherical

copper mirror 33 to the plane of photosensor matrix (matrix of pyroelectric sensors PYROCAM, production of Spiricon Inc., USA) 37. The matrix was registering either the distorted or corrected beams of 10- μ m radiation.

The beam of CO₂-laser 31 was adjusted with the use of visible radiation of He-Ne laser 34. Its radiation was reflected by the mirror 35 and by removable mirror 36 (three-point removable system, absent during system performance) and thus co-directed with IR radiation beam.

The modulator 10 was fed by periodical voltage (rectangular pulses with duration 50 ms and period 100 ms; see Fig.14, upper curve), and hence the beam of blue radiation, diffracting from this modulator (scaled down probe wave) was pulse-repetitive (Fig.14, lower curve). The use of CW reference wave of blue radiation would thus result in reduce of contrast of interference pattern at SLM 29. The synchronization of probe and reference waves of blue radiation was provided by shutter 23. It was comprised by electrically controlled LC SLM, mounted in crossed polarizers. Both beams (probe and reference) passed through this shutter. It was opened for 29 ms with the period 1 second. The opening pulse was delayed in 70 ms with respect to the pulse, feeding the SLM 10. So only the peak part of diffraction from this SLM passed through the shutter 23 and the synchronous part of CW reference wave was separated by the same element. SLM 29 was fed by pulses with duration 0.29 sec and repetition period 3 sec. Shutter was also serving as the polarizer of blue radiation.

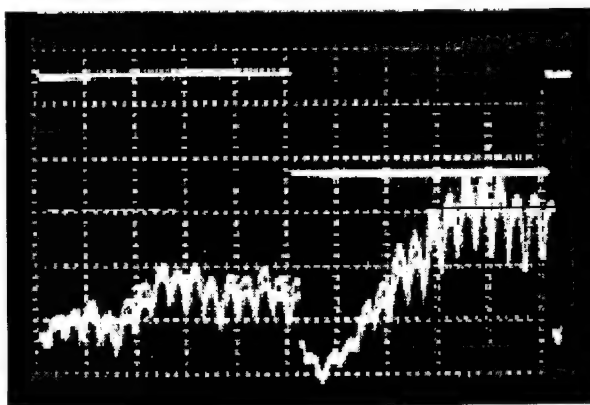


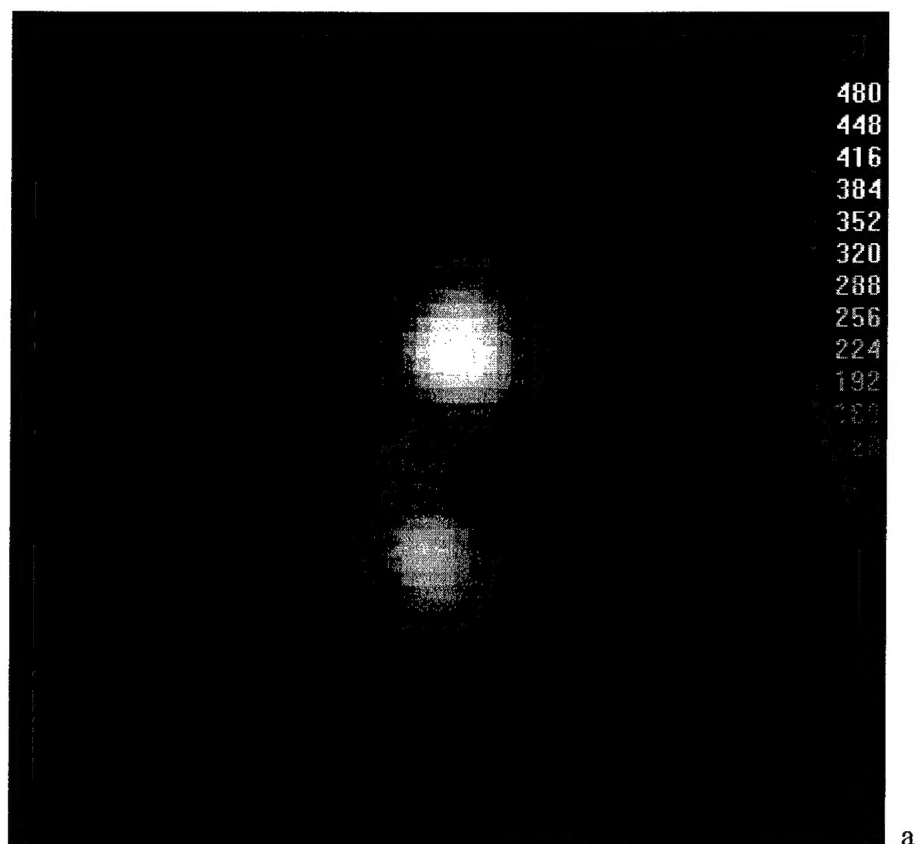
Fig.14. Temporal dependence of voltage, applied to ferroelectric LC SLM 10 (upper curve) and response from dynamic hologram in LC SLM 10 (lower curve).

Diffraction efficiency of dynamic hologram in SLM 29 was further improved by use of filters 18 and 30, equalizing the intensity of all the recording beams and providing

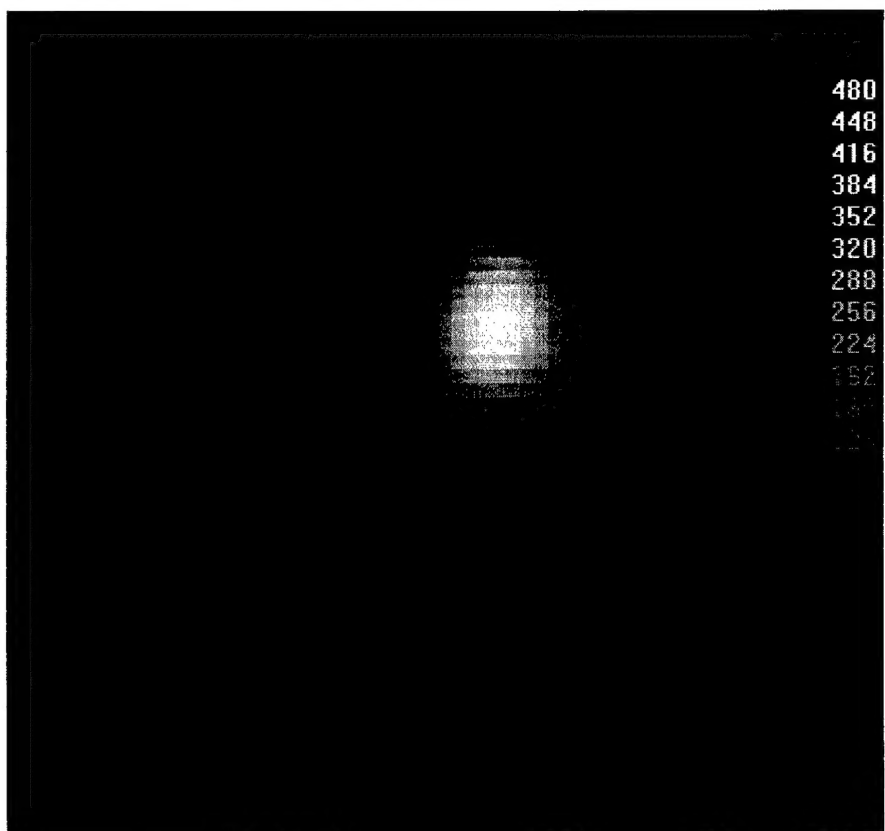
the optimal intensity level. The corresponding part of setup was covered by the protective case so as to eliminate the parasitic influence of daylight and scattered laser radiation onto very sensitive chalcogenide photoconductor of SLM 29. All these measures made it possible to realize in the correction setup the diffraction efficiency for mid-IR radiation of $\sim 1\%$ to working first order.

The results of experiments are shown in the Fig.15 and 16, presenting the far-field intensity distributions, registered by the system PYROCAM. In the Fig.15a and 16a are shown the far-field distribution of the zero diffraction order from dynamic hologram in SLM 29, registered for two different angles between the segments of mirror 11. In the Fig. 15b and 16b are shown the far-field distributions of the first diffraction orders, obtained for the same conditions as in Fig.15 and 17 correspondingly. (Intensities of beams were attenuated so as to fill into the dynamic range of PYROCAM).

One can see the practically complete correction for angular mismatch of two beams. These results confirm the feasibility of the concept of dynamic correction for distortions in mid-IR by means of differential two-wavelength dynamic holography, using the dynamic converter of distortions' scale.



a



b

Fig.15. Far -field mid-IR radiation intensity distributions of zero (a) and first (b) diffraction orders from SLM 29

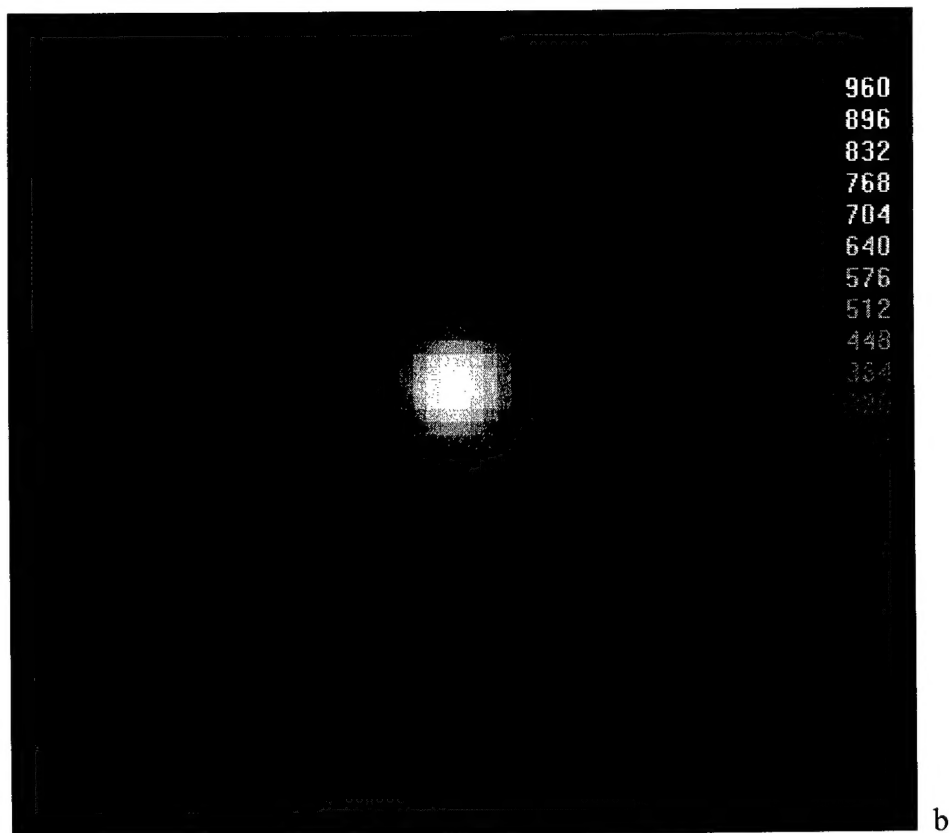
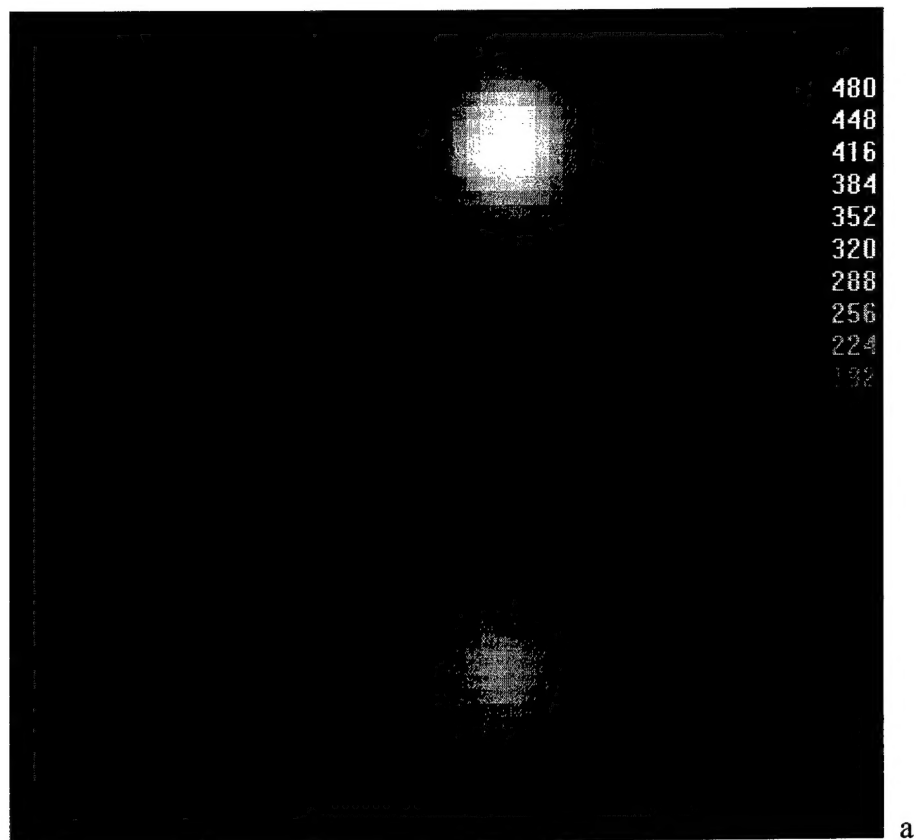


Fig.16. Far -field mid-IR radiation intensity distributions of zero (a) and first (b) diffraction orders from SLM 29

Conclusions

1. In course of work were analyzed and developed several concepts of nonlinear adaptive optics, based on use of two-wavelength dynamic holography, including:
 - a) the concept of dynamic holographic correction in mid-IR spectral range using the differential two-wavelength dynamic holographic corrector, recorded by visible radiation of two-wavelength auxiliary laser system;
 - b) the concept of negative feedback correction with the extended range of magnitude of corrected distortions;
 - c) the concept of simplification of the procedure of the measuring of the robust wavefront distortions.
2. The scheme of two-wavelength dynamic holographic converter of distortions scale was tested and confirmed in experiment.
3. The scheme of dynamic holographic correction in mid-IR spectral range using the differential two-wavelength dynamic holographic corrector, recorded by visible radiation of two-wavelength auxiliary laser system was tested and confirmed in experiment.
4. Pioneering specimens of optically addressed liquid crystal spatial light modulators (OA LC SLM) of special design, providing controlling the mid-IR radiation, but addressed by visible radiation, were developed, fabricated and tested. Two specimens of such elements were delivered to the Customer. On the base of these studies were developed and formulated the proposals on further development of technology of fabrication of such elements for the spectral range 3-5 μm .